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Ensemble Prediction of Inundation Risk and Uncertainty arising from Scour (EPIRUS): An Overview

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ABSTRACT: This paper presents a robust and integrated "Cloud-to-Coast" ensemble modelling framework which includes the complex interactions between atmosphere, ocean and coastal flood and erosion, so that the flood risk in the coastal areas from the extreme events, such as severe storms, can be accurately predicted and assessed. The associated uncertainties are examined by creating ensembles of possible future storm events.

1 INTRODUCTION

In the UK coastal flood defences are usually designed to withstand events with a return period of between 50 to 200 years, taking account of sea level rise. In 2006 the UK Natural Environmental Research Council (NERC) initiated a £5m research programme on flood risk under extreme events (FREE) to fund research into flooding arising from extreme events (> 50 year return period).

The interactions between atmospheric, oceanic and coastal processes are poorly understood, resulting in large uncertainties in the performance of sea defences and predictions of coastal flood risk in extreme conditions. NERC has funded the EPIRUS project to bring together a team of hydrometeorologists, oceanographers and coastal engineers to address this issue.

2 METHODOLOGY

This project integrates three different types of models, these are:

2.1 *Meteorology model*

The ensemble regional weather forecasting system will consist of the PSU/NCAR MM5/WRF and Met. Office UM mesoscale models and the global analyses/forecast datasets from the ECMWF. A dynamical-downscaling approach is being applied to resolve the dynamics over 1km grids. Based on these models and ECMWF ERA 40 Datasets, extreme weather futures will be generated with and without climate change and used to drive the coastal models.

The MM5 is the fifth generation NCAR/Penn State Mesoscale Model able to produce meteorological forecasts with high temporal and spatial resolution (NCAR, 2008; Dudhia et al., 2003). The MM5 requires initial and lateral boundary conditions from a global numerical weather model. This data set can be obtained from the European Centre for Medium Range Weather Forecasts (ECMWF, 2008). ECMWF also provides re-analysis data from past events, in particular the ERA40 data set, which covers from 1957 to 2002. From this data set, two extreme events have been identified, the 1990 and 1987 storms (see figure 1).

The MM5 was set up using a four-domain configuration. The domains are nested, with the largest coarse domain (domain1) being the input to the second domain and this to the third domain and so on.

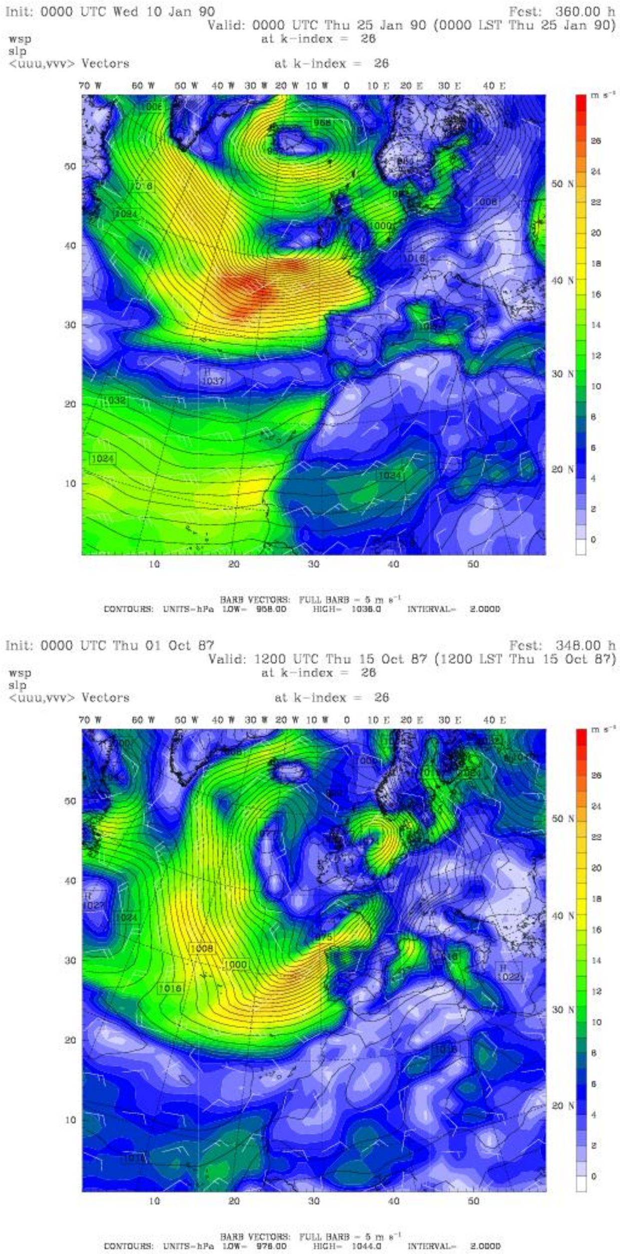

Figure 1. top - 1990 and bottom- 1987 storms (wind and pressure fields).

The ERA40 reanalysis data have a spatial resolution of 2.5x2.5 degrees every 6 hr. This data set comprises surface and pressure level data. There are two options in MM5 simulations: with or without four dimensional data assimilation (FDDA). The results reported here are based on no FDDA so that only initial and boundary conditions are taken in account. A comparison between with/without FDDA will be carried out in the next stage of our study and the impact of FDDA on the wind field and sea wave/surge simulations could be assessed. FDDA will be performed by nudging the wind, temperature and humidity or any combination between them. In FDDA, Newtonian relaxation terms are included in the prognostic equations for wind, temperature and humidity, so that the terms relax the simulations to a given analysis (See Stauffer and Seaman, 1990). This allows the MM5 to dynamically downscale the ERA40 data set for the required simulation period.

Figure 2 shows some results obtained without FDDA. Work is currently underway to set up the MM5 with the FDDA option and the comparative results will be reported soon.

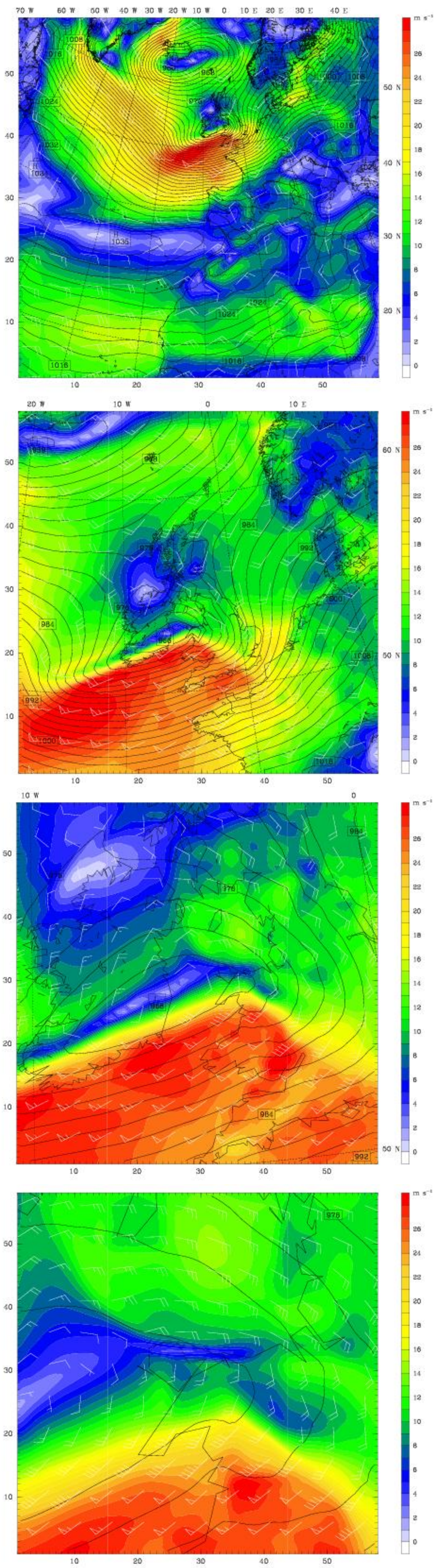

Figure 2. MM5 simulation (wind speed with sea level pressure contours) driven with ERA40 data set using initial and lateral boundary conditions only (no FDDA). Top:Domain 1; middle top: Domain 2; middle bottom: Domain 3; bottom: Domain4.

2.2 *Tides, Surge and Waves model*

Tide, surge and wave modelling forms a bridging part of the EPIRUS project. The main objective of this part of research is to quantitatively transform the meteorological parameters to oceanic and coastal waves and tides including the surge using a set of well-established models with different temporal and spatial scales. The results will be consequently used as boundary conditions for studying the wave overtopping and erosion, and to assess the flooding risk in the surf zone. The integrated tide, surge and wave modelling system consists the following components, a schematic diagram of which is shown in Figure 3:

1) Atlantic WAM model (oceanic scale) to provide wave forcing for regional models (~1000s km);
2) POLCOMS (regional scale), taking the regional meteorological information (wind and atmospheric pressure) to provide waves, swell and surges for local models (~100s km);
3) COAST2D (coastal zone scale) to provide further detailed hydrodynamics in the coastal zones, and to provide conditions for coastal flooding and erosion studies (~10s km).

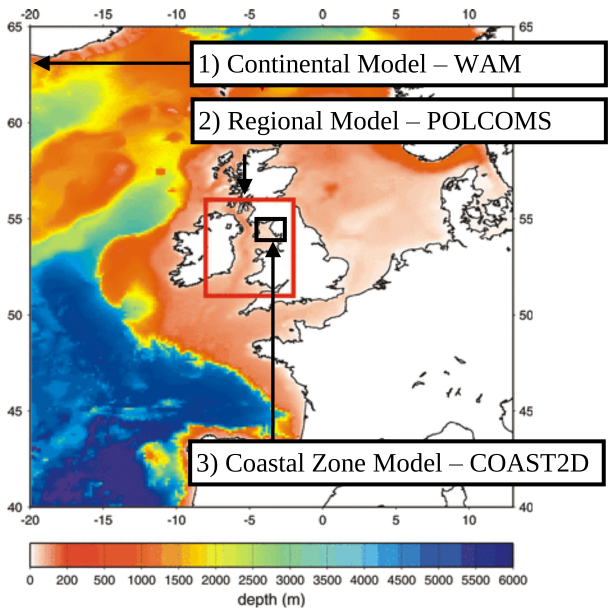

Figure 3. Schematic diagram of the modelling system.

The POLCOMS model has been developed at Proudman Oceanographic Laboratory (POL) for many years and is a baroclinic three-dimensional current model with coverage of both the deep ocean and the continental shelf. Further details of the model can be found in Holt and James (2001). The model recently incorporates the third-generation wave model, ProWAM, with an option of two-way coupling to quantitatively predict waves and currents (Wolf et al. 2002). The outputs of the POLCOMS model will provide the boundary conditions to drive the COAST2D model with a much finer resolution, for modeling nearshore coastal processes.

The COAST2D model includes the main nearshore coastal processes, such as wave refraction/diffraction, breaking, reflection, tides, wave-current interaction, taking offshore wave, tide and storm surge conditions from POLCOMS. The phase-resolving wave module has recently incorporated to take account of reflection due to the defence structures such as breakwaters and sea walls. Further description can be found in Pan et al. (2007). The COAST2D model will be used in conjunction with POLCOMS to predict the detailed nearshore wave and current climates at specific sites, and to provide the hydrodynamic conditions to the surf zone models for studying coastal flooding and erosion.

As a preliminary application, the modelling system was setup for the Irish Sea and at the Blackpool site. The POLCOMS model covers an area from 51^o N to 56^o N latitude and from 7^o W to 2.7^o W longitude, with a spatial resolution of 1/60^o by 1/40^o in latitude and longitude directions respectively. The coverage area of the COAST2D model is about 50 km cross-shore by 40km alongshore nearby Blackpool, with a much finer resolution of 250m by 250m in cross-shore and alongshore directions, respectively. The bathymetry of the nested domains is shown in Figure 4.

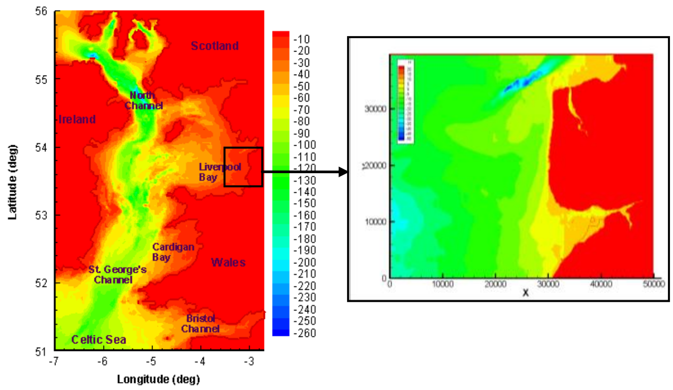

Figure 4. Bathymetry of the Irish Sea region for POLCOMS and the Blackpool site for COAST2D

The wave conditions for the POLCOMS model were generated by running a stand-alone WAM model, covering part of Northeast Atlantic Ocean (NEA), and the tidal conditions were provided by an implementation of POLCOMS for the northwest European continental shelf. The surface forcing for the POLCOMS model was provided by surface winds and atmospheric pressure in the Irish Sea region with a 1^{o}X1^o resolution at six-hourly intervals (ERA40 reanalysis). The same dataset was also extrapolated for the surface forcing required by the WAM model in the coarse grid.

Results of the significant wave height, surface elevation and depth-averaged tidal current obtained from the POLCOMS model are shown in Figure 5. It can be seen that the model responds well to various boundary forcings. The tidal elevations at selected points in the POLCOMS computational domain were taken as the boundary conditions required by the COAST2D model. The wind field provided by the meteorological models was also used in COAST2D as surface shear boundary condition.

Preliminary results obtained from the COAST2D model, which provides more detailed wave and tidal information in an area centred at Blackpool are shown in Figure 6. The figure shows that detailed tidal current velocities and wave height are reproduced in a local coastal and estuarine area with finer bathymetry. Once validated, these results will provide necessary boundary conditions for next level of predictions on the risk of coastal flooding and erosion.

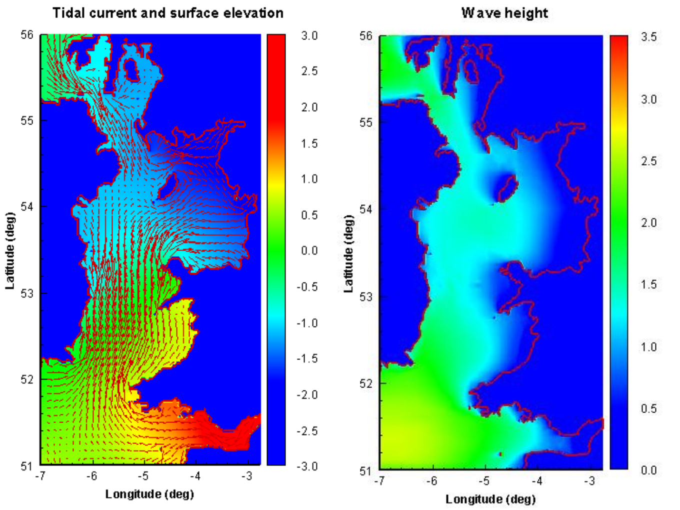

Figure 5. Computed tidal currents and tidal level (a), and wave height (b) from POLCOMS & ProWAM

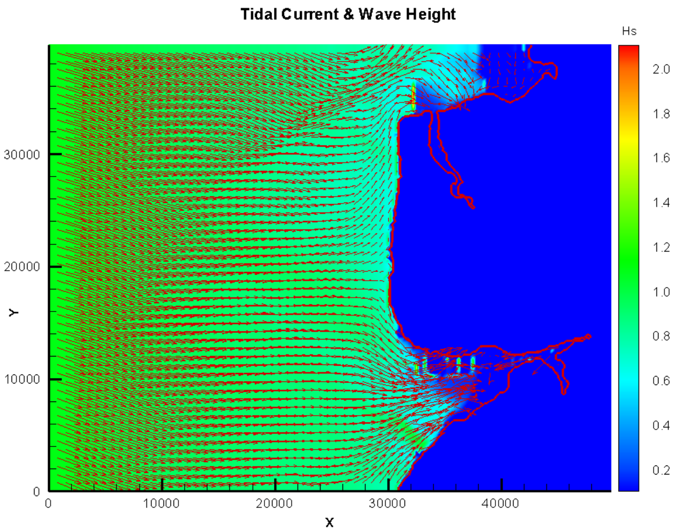

Figure 6. Computed current velocities and wave height from COAST2D

2.3 *Surf-zone model*

We are using a state-of-the-art surf zone hydrodynamics model, based on Reynolds-averaged Navier-Stokes equations (RANS) to determine wave overtopping, breaking, turbulence and streaming arising from the wave and water level outputs from the tide/surge/wave models. This model includes a free surface tracking scheme using the Volume of Fluid technique. For this project, it will be extended to include predictions of beach morphology.

In this section, results from model simulations of irregular wave overtopping of impermeable seawalls with slope of 1:3 are presented. More specifically, cases of positive freeboard are considered for slope of 1:3 with the focus being on comparing the model results with the empirical formulae. A total of 6 tests were run with a water depth of 4.5 m, dimensionless freeboard (R) ranging from 0.39 to 0.98 and irregular breaking waves with a JONSWAP spectrum with significant wave height (Hs) = 1.22 m, mean wave period (Tm) = 3.8 s and peak wave period (Tp) = 5.0 s. Details of the dimensional and dimensionless freeboard are shown in Table 1. Snapshots of the free surface after 80, 81, 82 and 83 s are shown in Figure 7.

The computational domain is discretized by an unstructured grid with in total 24,558 node points and 107,232 tetrahedral elements. The value of γ in the JONSWAP spectrum is set to 3.3 and the spectrum is represented by 91 component frequencies between 0.005 and 0.55 Hz. The random wave maker is placed at the left boundary and non-slip wall condition is used for all of the rest boundaries. Simulations are performed with a basic time step of 0.02 s, to generate time sequences with a total duration in excess of 500 s (corresponding to approximately 100 waves).

Table 1. The dimensional and dimensionless freeboard over a 1:3 sloped seawall for positive freeboard.

Run no.	Rc (m)	R[-]	Slope
1	0.900	0.39	1:3
2	1.125	0.49	1:3
3	1.350	0.59	1:3
4	1.575	0.68	1:3
5	1.800	0.78	1:3
6	2.250	0.98	1:3

Figures 8 and 9 show the cumulative total and mean overtopping volume calculated by the numerical model. The units of overtopping volume are m^3/s per metre-run, or m^2/s.

The unsteady nature of the overtopping events is clear from Figures 8 and 9 showing that the variation in the mean overtopping volume reduces rapidly and becomes very modest after the first 40 waves.

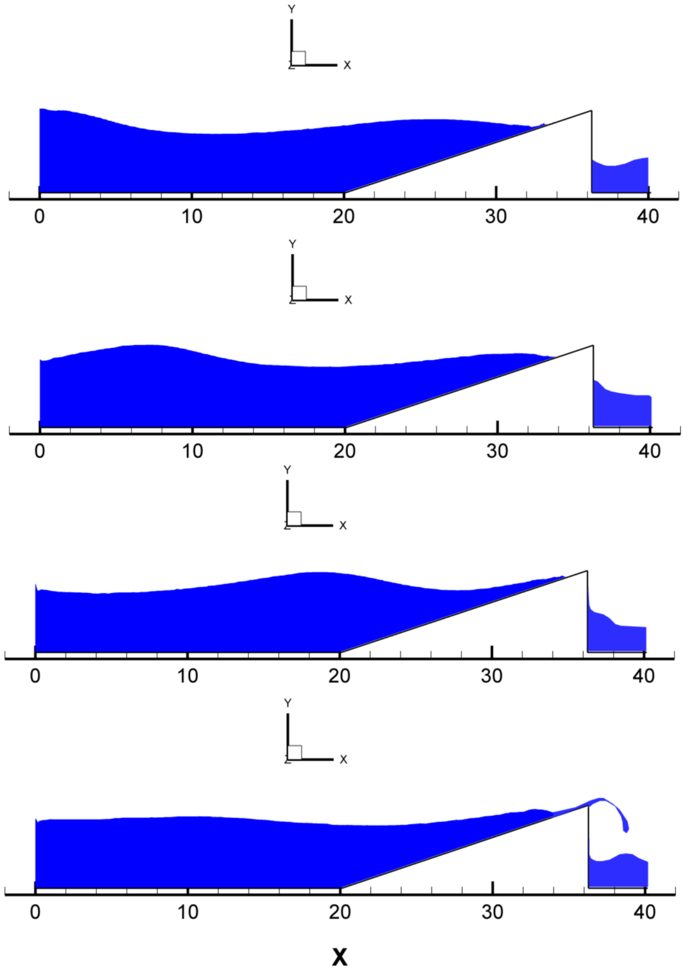

Figure 7. Instantaneous snapshots of breaking wave overtopping from top to bottom at t = 80, 81, 82 and 83 s, for a 1:3 sloped seawall, freeboard $R_c = 0.9$m.

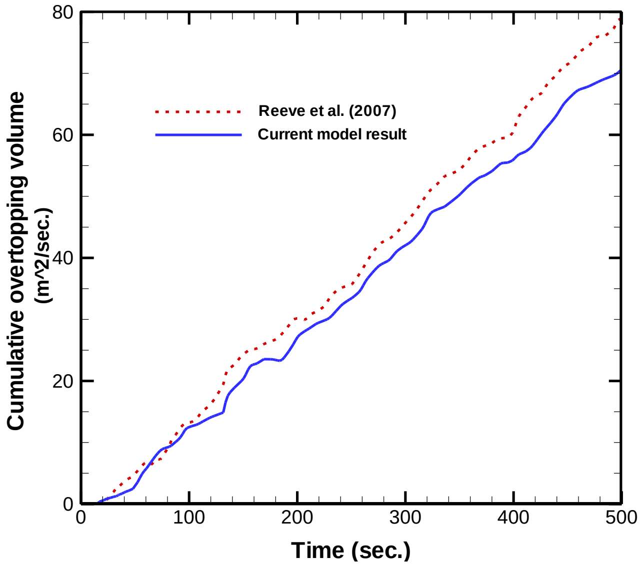

Figure 8. Time history of the cumulative overtopping volume for 1:3 sloped seawall, freeboard Rc = 0.9m.

A summary comparison between results from the numerical model and the empirical equations of Owen (1980), Hedges & Reis (1998) and Van der Meer & Janssen (1995) for the six cases are shown in Figure 10.

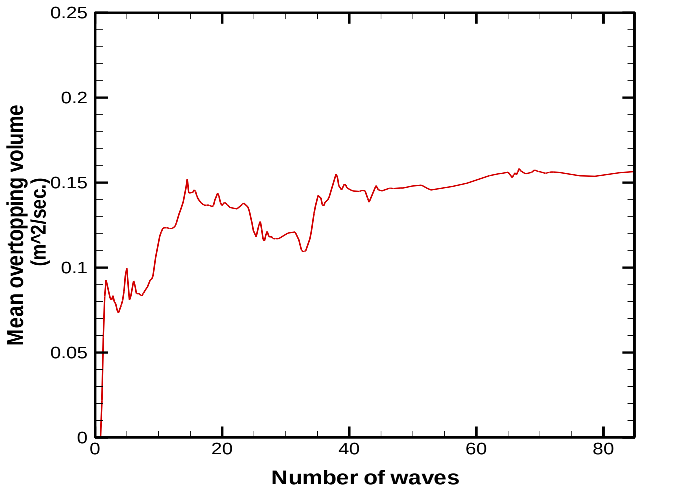

Figure 9. Time history of the mean overtopping volume for 1:3 sloped seawall, freeboard $R_c = 0.9$m.

Lines corresponding to the roughness scaling coefficient equal to 0.5 and 1.0 for the Van der Meer & Janssen formulae are shown. The majority of the numerical model results are slightly larger than the corresponding predictions from empirical formula but slightly smaller than the results by Reeve et al. (2007).

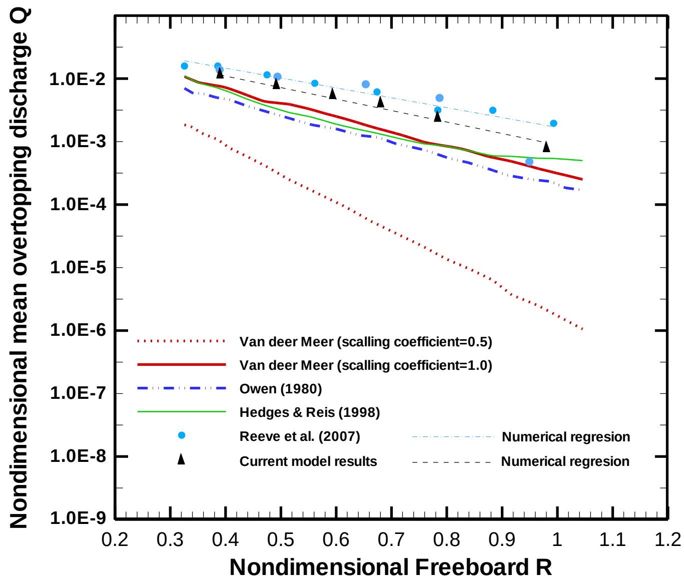

Figure 10. Comparison of numerical results, regression curves, Van der Meer and Janssen (1995) and Owen (1980) design formula for 1:3 sloped seawalls, dimensionless freeboard R ranges from 0.39 to 0.98.

3 MODEL INTEGRATION

For each member of an ensemble of past/future storms events, the predicted wind and pressure fields by the meteorology model will be used to drive the wave/surge/tide models. These give forecasts of off-shore wave and mean water level, which in turn are used to drive the surf zone model to predict the beach and structure response and to establish ensemble predictions of coastal flood risk arising from overtopping and scour.

4 ACKNOWLEDGEMENTS

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